COMPONENT FRAGILIT₁ RESEARCH PROGRAM:
PRIORITIZATION AND D:MONSTRATION TESTING

G.S. Holman
C.K. Chou

This Paper was Prepared for Submittal to the
14th NRC Light Wat:r Reactor Safety
Informatio₁ Meeting
Gaithersburg, Maryland October 27-31, 1986

December ᵢ, 1986

Lawrence
Livermore
National
Laboratory

DISCLAIMER

COMPONENT FRAGILITY RESEARCH PROGRAM: PRIORITIZATION AND DEMONSTRATION TESTING

G.S. Holman
C.K. Chou

Lawrence Livermore National Laboratory
University of California
P.O. Box 808 / Livermore, California 94550

COMPONENT FRAGILITY RESEARCH PROGRAM: PRIORITIZATION AND DEMONSTRATION TESTING*

G.S. Holman and C.K. Chou

Lawrence Livermore National Laboratory
University of California
P.O. Box 808 / Livermore, California

ABSTRACT

Current probabilistic risk assessment (PRA) methods for nuclear power plants utilize seismic "fragilities" — probabilities of failure conditioned on the severity of seismic input motion — which are based largely on limited test data and on engineering judgement. As part of the NRC Component Fragility Research Program (CFRP), the Lawrence Livermore National Laboratory (LLNL) developed procedures for fragilities testing. These procedures were applied to evaluate actual seismic capacities of motor control center (MCC) electrical devices, to develop seismic "fragility curves" suitable for PRA application, and to suggest various methods of improving MCC seismic performance. In other CFRP activities, LLNL used "high-level" qualification data to develop fragility descriptions for selected equipment, and identified candidate components for future comprehensive fragilities testing using similar procedures.

1. Introduction

Current probabilistic risk assessment (PRA) methods for nuclear power plants utilize component fragilities which are for the most part based on a limited data base and engineering judgement. The seismic design of components is based on code limits and NRC requirements that do not reflect the actual capacity of a component to resist failure. In order to improve the present component fragility data base and establish component seismic design margins, the NRC commissioned a Component Fragility Research Program (CFRP). The CFRP is being conducted in two phases. Phase I has consisted of parallel efforts to (1) develop and demonstrate procedures for performing component tests to obtain new fragilities data, (2) identify through systematic grouping components influencing plant safety and therefore candidate for independent NRC testing, and (3) compile and evaluate existing fragilities data obtained from various sources. The results of these three

activities form the basis for a comprehensive evaluation of component behavior, based both on available data and on new testing, to be performed in Phase II of the program.

During Phase I, the Lawrence Livermore National Laboratory (LLNL) has performed component testing and prioritization, while the existing fragilities data base has been compiled by the Brookhaven National Laboratory (BNL). The specific objectives of the Phase I LLNL effort have been as follows:

Component Prioritization

● systematically identify and categorize electrical and mechanical components influencing plant safety, taking into account system and subsystem functional descriptions, operating and maintenance experience, expert opinion, past PRA results, regulatory concerns and existing test data.

● collect and utilize existing test data and operating experience to judge the relative seismic capacity of each component identified.

● identify "very important, low seismic capacity" components which then become priority candidates for future comprehensive testing.

Demonstration Testing

● develop procedures for component fragilities and seismic margins testing and demonstrate the effectiveness of these procedures through actual component tests.

● obtain useful fragilities and seismic margins data for the components tested.

● enhance understanding of failure mechanisms of the components tested.

Our Phase I demonstration testing program and component prioritization activities are documented in separate NUREG reports [1,2].

2. Component Fragility

"Fragility" is a term commonly used to describe the conditions under which a component (or, in general, a structure, a piping system, or piece of equipment) would be expected to fail. In this paper we are concerned with *seismic* fragility, in other words, what levels of seismically induced input motion would be required to cause component failure; it is important to keep in mind, however, that fragility can in principle be defined for *any* input condition affecting component performance. Failure can be characterized as either functional (e.g., erratic behavior, failure to perform intended function) or physical, or as the exceedance of some predetermined performance criteria (such as a limit given in a design code).

One interpretation of component fragility — which we will refer to as the "fragility level" — evolves from qualification testing. In seismic qualification testing, a component is subjected to input motion characterized by a specified waveform describing input level (seismic

acceleration) as a function of frequency. The component is "qualified" if it continues to perform its intended function when its response to this input motion -- the "test response spectrum," or TRS -- meets or exceeds pre-determined acceptance limits (the "required response spectrum," or RRS). In qualification testing, the TRS is usually measured at the component support points.

Although it may establish the adequacy of a component for a particular seismic environment, a successful qualification test does not directly provide data on what input motion levels actually result in component failure. This can be (and sometimes is) done by retaining the original input spectrum and then increasing the input *level* until "failure" (however it is defined) occurs. The TRS at failure represents the "fragility level" (or "ruggedness") of the component; the difference between the fragility level and the qualification level thus represents the seismic margin or "reserve capacity" of the component.

Fragility is described differently when used for PRA purposes or for other types of probabilistic analysis. In this case, the fragility of a component represents the probability of its failure -- or more rigorously speaking, the probability of attaining a defined "limit state" -- conditioned upon the occurrence of some level of forcing or response function. It may be expressed in terms of a local response parameter (for example, input motion at the component mounting location) or can be tied to a more global forcing function such as free field peak ground acceleration (PGA). Note however that when fragility is anchored to a forcing function, the further removed the component is from that forcing function, the more factors there are (such as structural response and soil-structure interaction) that must be considered in the fragility description.

The probability of failure is typically described by a family of "fragility curves" plotted at various levels of statistical confidence (see Fig. 1). The central, or "median" function represents the fragility analyst's best estimate of the "true" fragility of the component taking into account all significant factors which, in the analyst's judgement, might contribute to failure. The central point (50% probability of failure) on this curve represents the "median capacity" of the component; ideally, this probabilistic value would correspond with the deterministic "fragility level" of the component. The fragility function is a cumulative distribution usually characterized by a lognormal function with this median value and a logarithmic standard deviation β_R which describes the "random" variation in the parameters affecting fragility. In a description of seismic fragility, for example, this parameter might represent the differences in real earthquake ground motion compared to the input motion that a component is subjected to in qualification or fragilities testing. Note that the random uncertainty controls the slope of the fragility function; the less random uncertainty, the steeper the fragility function becomes. As random uncertainty is reduced towards zero, the fragility "curve" approaches a step function with its break point at the fragility level of the component.

The 5% function and 95% function in Fig. 1 represent the "modeling uncertainty" in the median fragility function. These bounds, which may also be referred to as 5% and 95% confidence limits, are based on the assumption that there is uncertainty in the *median* capacity; this uncertainty is characterized by a logarithmic standard deviation β_U. Simply stated, the 5% confidence limit implies the following:

- there is only a 5% subjective probability that the actual fragility *level* is less than the median capacity indicated for the 5% fragility function.

- there is a 95% subjective probability ("confidence") that the "true" fragility function for the component would be equal to or greater than the 5% function.

Modeling uncertainty, often described as "lack of knowledge" about the component in question, reflects the adequacy (or inadequacy) of information -- component damping values, for example -- used by the fragility analyst to form his judgements about component capacity. Thus, modeling uncertainty in fragility descriptions has a subjective rather than a "random" basis as is true in the statistical sense.

For any given component, empirically developing a statistically meaningful seismic fragility would require that a large population of identical components (e.g., several hundred or several thousand) be subjected to successively higher levels of acceleration and the distribution of failures (however "failure" is defined) be recorded as a function of acceleration level. Practical constraints on time and resources clearly make this infeasible for a single component under well-defined load conditions, let alone for the effectively infinite combinations and permutations of component type, manufacturer, mounting, and loading conditions that could be identified for actual nuclear power plants. Therefore, an alternative approach is necessary to experimentally gain an insight into fragility.

Our approach to assessing fragility takes advantage of the fact that for certain PRA applications, a limited or "lower bound" fragility description may be adequate. In a probabilistic analysis, failure occurs only when the probability distributions of response and fragility overlap; therefore, only the lower tail end of the fragility curve may be of interest from a PRA standpoint. For components having a high seismic capacity (high "ruggedness"), the overlap of the response and fragility distributions could conceivably be so small under all credible loading conditions as to imply that the probability of failure is negligibly low.

One method of developing a "lower bound" fragility is to estimate a so-called "HCLPF" (for High Confidence, Low Probability of Failure) capacity for the component that takes into account both the random and modeling uncertainty in the median capacity. The definition of HCLPF used in the CFRP is that adopted by the LLNL Seismic Design Margin Program, namely that value of the forcing or response function (in this case, seismic acceleration) for which we have "95% confidence" that the probability of "failure" is less than 5 percent [3]. If the median capacity of a component is defined by a peak acceleration with value A, the corresponding HCLPF capacity (i.e., HCLPF acceleration) is obtained from the following numerical relationship:

$$A_{HCLPF} = A \exp\left[-1.65\left(\beta_R + \beta_U\right)\right]$$

where β_R and β_U represent the random and modeling uncertainties, respectively. The median capacity A can be determined by component tests, either to actual failure or to some threshold or "cut-off" limit. The cut-off might be applied, for example, in testing certain components

whose actual median capacities were significantly above any response levels of regulatory interest.

The HCLPF capacity provides a practical means of addressing variations that inevitably arise between actual plant conditions and test conditions, variations that might otherwise be difficult to parametrically quantify by testing alone. For example, the random uncertainty β_R allows for variations in real earthquake motion compared to test input motion, variations in building floor response, or (e.g., for cabinet-mounted electrical devices) random variations in cabinet response. The modeling uncertainty β_U can account for variations in real damping values, or in component mounting conditions, or in the response of functionally similar components of different size or supplied by different manufacturers. These uncertainties can be quantified by systematically structuring test conditions in the form of "sensitivity studies" to investigating the effect of various parameters on the measured median capacity of the device tested. This was the basic approach taken in our Phase I demonstration tests.

The HCLPF approach has the added advantage that, in the absence of complete fragility data, a "lower bound" fragility can still be defined for a seismically qualified component by assuming its qualification level also represents its HCLPF capacity. Engineering judgement can then be applied to estimate the uncertainty parameters and thus make inferences about the median capacity.

Note that because the HCLPF capacity by definition presumes a five percent probability of failure, while "qualification" implies no failure, this approach tends to be conservative. It may in fact be overly conservative if qualification levels are low, as would be the case for many plants in the eastern United States. However, HCLPF capacities based on "high level" qualification data -- from plants in the western United States, for example -- can provide useful lower bound fragilities for plants having relatively low design basis earthquakes. The CFRP Phase I prioritization report [1] describes in detail how we used this approach to infer the actual capacity of selected electrical equipment.

In itself, the HCLPF capacity is a useful parameter on which to base regulatory decisions concerning seismic performance. However, extreme care must be exercised in selecting "reasonable" values of β_R and β_U when using a HCLPF capacity derived from qualification data to infer the actual capacity or "fragility level" of a component. The reasons for this are two-fold:

● as shown in Fig. 2, the slope of the fragility curve becomes more shallow as random uncertainty (β_R) increases. Therefore, the resultant median capacity on the 5% curve (and, for constant β_U, the inferred fragility level) also increases with increasing random uncertainty.

As shown in Fig. 3, however, if the fragility level of the component is known (e.g., from actual failure tests), then the HCLPF capacity derived from the median capacity decreases with increasing random uncertainty.

● similarly, as modeling uncertainty (β_U) increases, the offset between the 5% fragility function and the 50% function also increases, implying an increase in the inferred fragility level. If, on the other hand, the fragility level is known, an increase

in modeling uncertainty drives the HCLPF capacity towards lower (i.e., more conservative) values.

The above exercise illustrates how a "bottom-up" approach towards estimating median capacity (i.e., inferred from HCLPF capacity) can imply that fragility level increases with uncertainty, which is clearly non-conservative. This observation suggests that the reverse approach -- basing HCLPF capacities on measured fragility levels -- is preferable for assessing seismic performance. For a given fragility level, such a "top-down" approach yields lower (i.e., more conservative) HCLPF capacities as uncertainty increases.

3. Component Prioritization

     In order to reduce to a manageable level the number of components included in a comprehensive test program, it was first necessary to review and prioritize components related to plant safety. Past efforts to develop generic minimum equipment lists through the use of probabilistic risk assessment models have met with limited success. The results of these efforts suggested that the apparent importance of components was strongly influenced by the component fragilities assumed in the analyses.

     The results of such probabilistic analyses can also vary widely from plant to plant, being strongly influenced by the specific event trees and fault trees used in the analysis. The reasons for these variations include the following:

●   event trees, which describe the postulated accident scenarios ("initiating events") potentially leading to core melt, depend on plant system design and operating procedures.

●   fault trees, which describe the sequences of equipment failure leading to core melt given that an initiating event has occurred, similarly depend on plant system design. Of particular importance are such factors as redundancy (e.g., duplicate systems, multiple trains within a given system, multiple systems of different design but with the same safety function), effects of partial failure, the potential for "common-mode" failure (e.g., independent vs shared power sources), and the "fragility" of the components in these systems.

     When assessing the influence of fault trees on the apparent importance of certain components, it is also important to consider that *component* failure may not necessarily constitute a "failure" in a safety sense. For example, the safety significance of seismically-induced contact "chatter" -- uncommanded state changes -- in a motor controller would depend on electrical circuit design and the characteristics of the mechanical device (e.g., a pump motor) that the starter was connected to. Consequently, although a particular starter may have a certain fragility (e.g., defined on occurrence of chatter), its "importance" in a safety sense could be very different from one plant (or, for that matter, from one system) to the next.

For any given component or component type, its fragility -- or probability of failure -- will itself depend on many factors that may vary widely from plant-to-plant. These include the following:

- manufacturer-specific differences in design, as well as random variations in performance from component-to-component.

- the particular failure mode identified and its relationship to plant safety.

- the "external interface" between the component and its environment, primarily component mounting conditions.

- degradation ("aging") caused by such factors as temperature, vibration, and radiation.

- input load characteristics, which are influenced by site-specific soil behavior and structural response (e.g., component location) as well as to random variations in seismic input motion.

Clearly, feasibility considerations limit not only our ability to empirically develop broadly applicable "generic" fragilities, but to identify individual components as being "most important" to plant safety.

In view of these limitations, we took an alternate approach to systematically identify, categorize, and prioritize electrical and mechanical components. We based this approach primarily on the design of "typical" plant systems under both normal and abnormal operating conditions, supplemented by expert opinion on plant operating experience, past PRA results, and the results of industry qualification testing. The general approach taken in this effort proceeded in the following steps:

1. Identify "safety functions" necessary to maintain a plant in a safe condition ("normal operation"), or to safely bring the plant to and maintain it in a state of cold shutdown in the event of an earthquake ("accident mitigation").

2. For each safety function, identify associated plant systems (or sub-systems, as appropriate). The systems considered included those having only a normal operating function, those having only a designated safety function (i.e., for accident mitigation), and those having both operating and safety functions.

3. For each system, list major components based on system descriptions. Here "components" included items generally regarded as mechanical or electrical equipment. Such items as piping, tanks, heat exchangers, equipment supports, and structures were not included.

4. Within each system, group components according to whether they are "very important", "important", or "less important" to the system being able to perform its designated safety function.

5. Within each system, identify "high-", "intermediate-", or "low-capacity" components based on the anticipated ability of each to function during a postulated earthquake.

6. Rank each component by combining its importance and seismic capacity.

The specific criteria for defining importance and seismic capacity are outlined in the following discussion. The general process resulted in nine natural groups, that is, three levels of seismic capacity for each importance group. Those components ranked as "very important, low-capacity" became first-priority candidates for Phase II testing, while "important, low-capacity" or "very important, intermediate-capacity" were assigned as second-priority candidates.

The actual systematic prioritization of components was performed by a Component Identification Working Group formed of expert consultants from a wide range of engineering disciplines. The working group members were drawn primarily from the nuclear industry, and represented a number of nuclear steam supply vendors, architect-engineering firms, and utility owner-operators. The following discussion briefly summarizes describes how our prioritization of components was developed.

Plant Safety Functions

The following plant functions were assumed to contribute to plant safety, either during normal operation or accident mitigation, or both:

1. Control reactivity
2. Control reactor coolant inventory
3. Maintain integrity of the reactor coolant pressure boundary
4. Maintain adequate core cooling
5. Remove decay heat
6. Maintain plant environment
7. Maintain containment integrity
8. Maintain adequate supply of electrical power
9. Provide control and instrumentation
10. Maintain vital auxiliaries

Plant Safety Systems

Table 1 lists the plant systems considered in this evaluation, organized by safety function; for each safety function a system-by-system breakdown of components was then developed for consideration. The component list was based primarily on a review of system descriptions for Zion, a four-loop Westinghouse PWR plant. As a result, the systems considered tend to be PWR-oriented, although certain systems unique to boiling water reactor (BWR) plants were considered as well. Despite the strong PWR emphasis, we regard the resultant prioritization of components as reasonably representative of all plants, due to the fact that the *relative* importance of *systems* -- which may vary widely from plant-to-plant -- is not taken into account.

Component Importance

For each system listed in Table 1, components were ranked according to their effect on the ability of that system to perform its intended safety function. No consideration was given to the relative importance of any one system compared to another, as this is highly variable from plant-to-plant. As discussed earlier, past attempts to use PRA techniques for defining "generic" importance lists have in fact indicated that the relative importance of plant systems is strongly dependent on the component fragilities assumed in the assessment.

After components were identified for a particular system, each was assigned to one of three importance groups -- very important ("VI"), important ("I"), or less important ("LI") -- according to the following guidelines:

Very Important: failure of the component would prevent the system from performing its designated function. In other words, component failure implies system failure.

Important: failure of the component results in a significant reduction in system performance.

Less Important: failure of the component would not significantly affect the performance of the system.

Note that component "importance" or "safety significance" as used in this development is not intended to necessarily correspond with or to redefine equipment "important to safety" as used in NRC terminology. The assignment of a component to a particular importance group was based on the subjective judgement of the working group members.

In principle, the relative importance of a given component (or type of component if more than one are present) to a particular system could be affected by redundancy and by component performance character- istics. For example, if a pump is able to deliver only 50 percent of its rated flow, the relative importance of that pump would depend on how the flow reduction affects the ability of the overall system to perform its function, taking into account such factors as number of flow trains and the discharge capacities of other pumps in the system. Our prioritization scheme, however, recognized neither partial failure nor redundancy of components. The latter factor implies that common- mode failure is an important consideration; therefore, even redundant components may be categorized as "very important."

Seismic Capacity

Component seismic capacity was characterized by local zero period acceleration (ZPA) at the component support location. The local response spectrum was assumed to be characterized by a relatively broad- band frequency content, with a ZPA of 2g (or greater) being postulated as an important threshold to denote "high capacity" components. For realistic definitions of earthquake ground motion and structural response, this local threshold (if considered as a structural floor response) is expected to encompass earthquakes inducing up to 1g peak ground acceleration (PGA) in the free field. For our purposes, three "capacity levels" were identified:

Level 1: component is expected to remain functional for local response greater than 2g ZPA ("high capacity").

Level 2: component "failure" is anticipated for local response between 1g and 2g ZPA inclusive ("intermediate capac- ity").

Level 3: component "failure" is anticipated for local response less than 1g ZPA ("low capacity").

where "failure" might be defined as either functional or physical
failure, or both. Note that no detailed verification was undertaken of
earthquake ground motions corresponding to Levels 1, 2, and 3 of local
response, as this would depend on plant-specific structural and geolog-
ical characteristics. Note also that the precise definition of "local
response" depends on the particular mounting characteristics of the
component in question. For example, the appropriate "local response"
for motor control center (MCC) internals (e.g., relays, contactors)
would be the in-cabinet response at each device location, while that
for the MCC as a whole would be the structural "floor response" at the
cabinet base.

Comparison Against Data

Tables 2 through 4, respectively, summarize all low-, intermed-
iate-, and high-capacity components identified in this evaluation,
arranged according to importance group. After the reviewed components
had been subjectively ranked by importance group and anticipated seis-
mic capacity, a comparison was made with available qualification data
as a check on the subjective seismic capacity level. The main source
of data used for this purpose was a summary of qualification test
results for Millstone Unit 3 (a Westinghouse PWR) provided by Northeast
Utilities. This data was supplemented by similar data taken from a
seismic re-evaluation program performed by the Pacific Gas & Electric
Company for Diablo Canyon Units 1 and 2 (also a Westinghouse PWR)
following discovery of the previously undetected "Hosgri" earthquake
fault near the plant site.

Note that the "qualification level" for a particular component
relates its performance at a specific test input level which in turn
reflects the design basis earthquake for the plant site. It is *not* the
"fragility level" of the component, and may in fact be an overly conser-
vative representation of the point at which component "failure" would
actually occur. As a result, a review of qualification data alone may
not be sufficient for assessing the ultimate seismic capacity of
certain plant equipment. For example, the "high capacity" rating of
the certain components was supported by the Millstone qualification
data despite the relatively low (0.18g) SSE requirement. Consequently,
the subjective ranking of these components as "high capacity" appears
to be reasonable. Not surprisingly, however, much of the Millstone
qualification testing did not reach the 2g threshold ZPA that we had
designated for Level 1 components owing *to* the low SSE requirement.
Furthermore, when "high level" qualification data was considered for
some components -- in this case from the PG&E evaluation program for
the 0.75g Hosgri SSE -- markedly different seismic capacity levels were
often inferred.

Such discrepancies in inferred capacity more likely reflect test
input rather than "actual" component capacity. If this is indeed the
case, HCLPF capacities based on the low-level qualification data would
clearly yield conservative -- perhaps overly conservative -- descrip-
tions of component fragility. Conversely, if the "high-level" data can
be shown to apply to equipment at the "low-level" plant site, then
substantial margin between design basis and actual ultimate capacity
would be demonstrated. Of course, the applicability of "high level"
qualification data to plant equipment qualified for significantly lower
SSE levels depends on the extent to which the equipment in the high-
level tests was modified specifically to meet the higher SSE require-

ment as well as to other factors such as differences in mounting conditions.

It therefore remains to identify a suitable technical basis for resolving these discrepancies in inferred seismic performance. Two avenues are available for this purpose:

● detailed evaluation of existing data, preferably actual fragility data or, alternatively, high-level qualification data.

● fragility testing specifically structured to investigate the effects of various factors (e.g., mounting) on seismic performance.

In either case, the evaluation must address not only the "commonality" of like equipment at high- and low-level plant sites, but also specific factors (e.g., mounting) that potentially affect seismic performance. Typically, these factors are not systematically investigated as a part of qualification testing; any "sensitivity studies" performed during such tests generally arise out of necessity as equipment is modified in order to meet qualification requirements.

To demonstrate how "high-level" qualification testing can be used to assess ultimate seismic capacity, we developed fragility descriptions for five components based on high-level qualification data from the Hosgri requalification program. Although not true "fragility" data, these test results provided valuable information on component behavior under conditions exceeding any anticipated change in peak ground acceleration for eastern plant sites. The specific equipment that we evaluated included the following:

● 4160-volt metal-clad switchgear
● potential transformer 4160/120VAC
● safeguard relay boards
● emergency light battery pack
● station battery and racks

To describe equipment fragility, we assumed that the qualification test results represented the "high-confidence, low probability of failure" (HCLPF) value for each. After a thorough review of test conditions and test results (particularly relating to cabinet transmissibility), we used our judgement to estimate the uncertainty and random variability in the fragility description. This, in turn, provided us with a basis for inferring the median capacity of the equipment being considered.

Besides providing a basis for developing probabilistic fragility descriptions, these tests yielded insight into the influence of such parameters as support arrangement, cabinet rigidity and mass distribution on seismic capacity. In some cases the results of these tests identified practical -- and often relatively minor -- hardware modifications which substantially improved the seismic performance of the equipment tested.

The results of our assessment, described in Ref. 1, indicated that high-level qualification data can be used to infer ultimate capacity ("fragility level") provided that sufficient information is available from which to estimate how factors such as component mounting affect seismic performance. Our evaluation further indicated that many

components included in the Hosgri evaluation were qualified in their standard commercial configurations or with relatively minor modifications. This result is encouraging because it suggests commonality among certain "standard" equipment items and therefore that high-level test results can be used to "confirm" seismic capacity levels -- at least for "high capacity" components -- assigned to like equipment at plants having lower SSE requirements.

However, as discussed earlier, such a "bottom-up" approach (i.e., fragility level estimated from HCLPF capacity) suggests that fragility level increases with uncertainty, which is clearly non-conservative. Extreme care must therefore be exercised in selecting the uncertainty parameters used to infer the component fragility level. Unfortunately, definitive information may not be available on certain factors potentially affecting seismic performance, such as component mounting, as these factors are not usually investigated systematically as a part of qualification testing; any "sensitivity studies" performed during such tests generally arise out of necessity as equipment is modified in order to meet qualification requirements.

This result implies that a "top-down" approach -- estimating HCLPF capacities from actual failure data measured in fragility tests -- is preferable for assessing seismic performance, particularly when developing detailed fragility descriptions for low-capacity equipment.

4. Phase I Demonstration Tests

As part of the Phase I CFRP, we performed actual tests to demonstrate our approach to fragility testing. The specific objectives of our Phase I demonstration tests were as follows:

● demonstrate, for a typical item of nuclear power plant hardware, that we could characterize its fragility.

● investigate the dependence of fragility on a specific "technical issue" affecting equipment behavior.

● generate useful information regarding the actual seismic capacity of the equipment tested.

● develop practical fragility descriptions based on the experimental data, suitable for application in probabilistic risk assessments.

● provide guidance for interpretation of test data available from other sources.

Although independent of our prioritization efforts, the Phase I demonstration tests also provided guidance on the level of effort necessary to do meaningful yet cost-effective fragilities testing, as well as on the level of detail appropriate for specifying candidate components for Phase II evaluation.

We selected as our test specimen a three-column Westinghouse Five-Star motor control center (MCC) containing 8 Westinghouse motor controllers of various types and sizes as well as 14 relays of different types and manufacturers. The Five-Star is the current basic model marketed by Westinghouse for industrial and power system applications; it is essentially identical to the Type W motor control center manufactured by Westinghouse from 1965 to 1975, various configurations of which are

found in many nuclear power plants of this vintage. The particular electrical devices selected represented a sample of standard MCC devices typical in function of those found in actual plants, but are not necessarily generic for all similar devices.

It is important to note that the selection of an MCC as our test specimen was made with no intent to "target" motor control centers out of any special concern. Instead, we viewed the MCC as having certain characteristics which would allow us to best demonstrate our general approach to fragilities testing. While our prioritization activities have generally identified MCCs (and their internal devices) as impor- tant components, our selection of an MCC for demonstration testing did not depend on its importance relative to other components.

As our "technical issue" of interest, we investigated the effect of base flexibility on electrical device behavior by systematically varying the mounting configuration of the MCC. Besides addressing the specific question of how base mounting might affect device behavior, testing with different mounting configurations offers the following useful insights:

- if device (e.g., relay) behavior as a function of local in-cabinet response varies insignificantly with changes in the mounting of the MCC, this result would imply that fragility data from tests on individual devices would also apply for the same devices mounted in cabinets.

- by correlating device fragility only to local in-cabinet response (in particular, ZPA) independent of MCC mounting configuration and device location, the scatter in the experimental results (and thus the uncertainty in fragility descriptions developed from the data) should encompass such issues as variations in cabinet transmissi- bility and in-cabinet device location.

In these tests we investigated both the functional behavior of the individual electrical devices -- relays and starters -- and the struc- tural response of the MCC cabinet for various levels of table input motion and for four different cabinet mounting configurations, although the cabinet itself was viewed mainly as a "typical" load transmission device between the floor and the devices. We conducted multiple tests on each of the following four mounting configurations: four bolts per column with top bracing, four bolts per column with no top bracing, four bolts per column with internal diagonal bracing, and two bolts per column with no top or internal bracing. We performed a total of 56 test runs, including 43 biaxial random motion tests (vertical plus one horizontal axis). Table input motions in the random motion tests ranged up to 2.5 g zero period acceleration (ZPA), which yielded in- cabinet spectral accelerations up to 10 g and higher at the device locations.

Functional Behavior

We used contact "chatter" -- contact motion causing a momentary uncommanded change of state -- to characterize the functional behavior of each electrical device tested. For qualification purposes, chatter is usually defined as any uncommanded state change longer than a spec- ified duration; the occurrence of chatter therefore indicates "failure" of the device. In our investigation, we did not test to pre-determined

acceptance criteria, but instead recorded for each device the following parameters related to its functional behavior:

- the <u>number</u> of chatter events. Single events, such as momentary "bouncing" of contacts, often occur as a normal part of commanded state changes and therefore may not represent true chatters.

- the <u>duration</u> of individual chatter events. In our demonstration tests, we categorized chatter events according to duration, ranging from 2 ms (the threshold typically applied in qualification tests) to over 80 ms.

- the effect of <u>device state</u> on occurrence of chatter. Past tests on similar devices have indicated that spurious contact motion is highly dependent on whether or not the contact coil is energized at the time strong motion occurs.

We later used these parameters as a basis for developing probabilistic fragility descriptions ("fragility curves") for each type of electrical device in the MCC, referencing fragility to local ZPA at the device location. In addition to "best estimate" descriptions of device fragility, we estimated the random variability and modeling uncertainty to arrive at a "high confidence, low probability of failure" (HCLPF) capacity for each type of device. Figure 4 shows a representative set of curves developed from the test data, in this case for the Westinghouse Type AR armature-type relays installed in the MCC.

Aside from providing a basis for developing probabilistic fragility descriptions, our MCC tests also lent insight into the functional behavior of contact-operated electrical devices subjected to extreme levels of seismic input motion. The more significant observations made from the results of these tests include the following:

- for all devices, chatter occurred only when the device contacts were in their deenergized state. Without exception, no chatter of energized contacts was recorded.

- for all devices, virtually all chatter occurred when the MCC was tested in its front-to-back orientation. Only isolated instances of contact chatter were recorded when the MCC was tested in its side-to-side orientation; these were attributed to possible variations in local in-cabinet waveforms.

  Given the mounting orientation of most devices in the cabinet (i.e., direction of contact motion oriented with the front-to-back axis of the cabinet), these results imply that chatter is most likely to occur when the input motion is oriented with the direction of contact action. Virtually no chatter was observed when the input motion was oriented perpendicular to the direction of contact action.

- for starters, virtually all chatter occurred in auxiliary conacts. Only isolated occurrences of spurious main contact action were recorded, most of which could be attributed to contact "bounce" during a commanded state change.

- for all devices, normally-closed contacts consistently chattered at lower input levels and more often than normally-open contacts. This suggests for these devices that contact chatter is caused by armature movement rather than local response of the contact element.

- neither reed-type relay was observed to chatter, regardless of input level or MCC mounting configuration. This observation was not surprising considering the extremely low contact mass of the reed-type relays compared to that of the armature-type relays tested.

- the occurrence of chatter appears to correlate only weakly with local in-cabinet ZPA. The significant overlap in "chatter" and "no chatter" in-cabinet response spectra implies that spectral acceleration may be a more appropriate parameter to define the "threshold" above which chatter occurs.

- all 14 relays and all 8 starters responded normally to commanded changes of state for all input levels and MCC support configurations. This held true for each device regardless of whether it was initially energized or deenergized. Only in one case did a device not respond to a commanded state change; this was attributed to technician error.

- the results of single-axis, single-frequency tests performed on one Size 2 starter and one relay removed from the MCC indicate that chatter is most likely to occur for input motions in the 2.5 to 8 Hz range. This result further supports the conclusion that spectral acceleration, rather than ZPA, is a more appropriate basis for characterizing device fragility.

Our fragility estimates indicated that the median capacity ("best estimate" curve, 50 percent failure probability) of the MCC relays ranged from 5.2 to 6.1 g local ZPA, with HCLPF values ranging from 3.2 to 4.3 g local ZPA. When considered as a single group, these relays have a median estimated capacity of 5.6g and a HCLPF of 3.6g. Keep in mind these are local in-cabinet levels, not the motion at the cabinet base, and that input motion is oriented in the direction of contact action. No fragility description was developed for the reed-type relays because no chatter was observed.

The test data for Size 2 reversing and non-reversing starters yielded identical median capacities of 3.9g, and HCLPF capacities of 2.5g and 2.3g, respectively. Note that these results reflect auxiliary contact chatter; for all practical purposes, no chatter of main contacts was observed. The similarity in behavior is not surprising when it is considered that reversing and non-reversing starters differ only in the number of contact sets used (two vs one); the contact sets themselves are identical. For the two Size 3 starters tested, the median capacity was 6.5g local ZPA. The markedly different capacity compared to that of the Size 2 starters most likely results from the substantial difference in starter size.

Note that these results assume that input motion is oriented with the direction of contact motion. The results of our tests indicated that virtually no chatter occurs when the direction of input motion is perpendicular to that of contact motion.

The results of our tests -- the random motion tests on the MCC as well as sinusoidal tests on two devices removed from the cabinet -- also imply that local spectral acceleration is a more appropriate parameter for describing device fragility than local ZPA. Nevertheless, the results of this study demonstrate how test data can be used to develop practical fragilities for PRA applications.

Structural Behavior

Vendor tests have shown that electrical devices such as those included in our tests typically show high resistance to structural failure; in other words, seismic excitation would be expected to affect functional behavior before any physical damage to the device occurred. Consequently, the only likely structural failures in our demonstration tests were those to the MCC cabinet itself. Types of possible damage anticipated included the following:

- non-destructive effects of cabinet shaking, such as cracking of paint.

- permanent, but non-destructive damage such as deformation of cabinet structures.

- cracking or breaking of welds, destruction of cabinet structures, pull-out or breaking of mounting bolts. Although outside the scope of our demonstration testing, pull-out of concrete anchors might also be expected to occur in actual plant applications.

We inspected the cabinet for signs of damage after each test. In later tests, as the likelihood of permanent cabinet damage increased, we also measured strain levels at selected locations on the cabinet frame. The more significant observations regarding structural behavior of the MCC cabinet include the following:

- our demonstration tests focussed on low-frequency input motions, i.e., less than 9 Hz. We found that with the brace at the top of the MCC, the resonant frequency of the cabinet frame was about 12 Hz, well above this level. Removing the top brace caused the front-to-back resonant frequency to drop to about 5 Hz. Reducing from four to two the number of mounting bolts per column further reduced the frame frequency to about 3.5 Hz.

  The effect of mounting configuration on cabinet response takes on added significance when the results of the single-axis single-frequency device tests are considered. The one relay and one starter tested both indicated highest sensitivity to input motions in the 2.5 to 8 Hz range. Removing the top brace from the MCC lowered the front-to-back frame frequency (i.e., in the direction of contact action for most devices in the MCC) from well outside this range to a point where it could conceivably have a signifi-cant effect on device behavior.

- the predominant resonances of the MCC draw-out units ("buckets") ranged from about 14 to 26 Hz, well outside the "sensitive" range indicated by the sinusoidal tests.

- we observed no cabinet damage when the MCC was braced at the top. Testing of the free-standing MCC in the side-to-side direction similarly caused no indication of structural damage until late in

the testing program. Although substantial damage was observed in later tests (in the form of cracked welds between the base frame and the vertical frame members), the cabinet nevertheless withstood some 20 strong motion tests at ZPA levels up to 1.9g before any significant damage was observed.

In general, our test results suggest that top bracing can increase the seismic capacity of both the MCC structure (by limiting cabinet motion) and the internal electrical devices (by increasing the resonant frequency of the cabinet frame).

5.   Summary and Conclusions

The results of our Phase I prioritization efforts provide guidance regarding not only the urgency of assessing the seismic performance of various mechanical and electrical components, but also the nature and rigor of assessment procedures appropriate for the component in question. Options available for detailed assessment include comprehensive testing -- such as the parametric motor control center tests that we performed in our Phase I demonstration test program -- or evaluation of existing data, or some combination of the two. Our Phase I efforts have demonstrated that if appropriate data is available, either from existing sources or from specially-designed fragility test programs, insights into component capacity *can* be obtained and serviceable fragility functions *can* be generated for PRA applications. The question that remains, however, is one of how definitive the resultant descriptions of seismic performance actually are.

As discussed earlier, a "bottom-up" assessment of seismic capacity (i.e., fragility level estimated from HCLPF capacity) suggests that fragility level increases with uncertainty, which is clearly non-conservative. The fragility analyst must therefore exercise extreme care when selecting the uncertainty parameters used to infer the ultimate capacity, or "fragility level", of a component. Unfortunately, the information necessary to select these parameters may not be available from existing data, or may be difficult to assess consistently if attempts are made to consolidate data from several diverse sources. The less definitive the data on HCLPF-derived fragility descriptions are based, the higher their degree of inherent uncertainty.

For certain high-capacity components, this uncertainty may be tolerable if only a "lower bound" fragility -- a HCLPF capacity, for example, or a 5% fragility function -- is adequate for regulatory decision-making or for PRA applications. This may apply, for example, to the five Diablo Canyon components considered in this assessment. This may also be true for high-capacity components at plant sites with relatively low SSE requirements (e.g., in the eastern U.S.), provided that (1) the "high capacity" rating of these components can be substantiated, and (2) commonality in configuration and mounting conditions can be established between the in-plant components in question and those for which "high level" data is available.

In general, however, high inherent uncertainty implies that a "top-down" assessment -- estimating HCLPF capacities from measured fragility levels -- is still preferable for assessing seismic performance. This is particularly true when a detailed fragility function, rather than a "threshold" fragility description, is necessary for low-capacity equipment. Parametric "sensitivity" tests, even on a limited scale, are

best-suited for this purpose when structured to systematically investigate how individual factors affect seismic performance.

Clearly, even for functionally identical components, variations among manufacturers and models, in size and type, and in mounting and loading conditions imply that any fragility estimate -- or, for that matter, other methods of assessing component performance -- will be based to a certain extent on engineering judgement. It is important that this judgement be supported by as firm a technical basis as possible within practical constraints. Our Phase I tests demonstrated that "testing for understanding" is a feasible and cost-effective means of assessing component fragility. This positive experience therefore suggests that Phase II tests be similarly conducted according to the following general steps:

(1)   identify a representative component or sample of components for testing. Such a sample might not necessarily be "generic" in the purest statistical sense, but should attempt to include significant variations within a given component type (armature- vs reed-type relays, for example).

(2)   identify failure modes and the relevant forcing or response functions. Characterize "failure" (either functional or physical) in terms of a suitable parameter that can be measured experimentally.

(3)   identify factors or "technical issues" affecting component failure; such factors might include, but not necessarily be limited to, variations in mounting, input motion, and component damping. Design experimental program to parametrically vary those factors judged to be important.

(4)   perform tests to identify when failure occurs, i.e., component median capacity. Such tests might, for example, follow qualification procedures (e.g., use of same input spectra) but at elevated input motion levels. Alternatively (particularly for "high capacity" components), test to a pre-determined level to establish a "lower bound" failure threshold.

(5)   use test results to empirically estimate median capacity; note that this result is equivalent to the deterministic "fragility level" generated as a part of some qualification tests. Based on component behavior over all conditions considered, develop estimates of random variability and modeling uncertainty in the empirically derived median capacity.

Although this approach does not remove subjectivity from the process of describing component fragility, it does improve the basis on which these judgements are made. Furthermore, it can provide information useful on many levels, including:

●   guidance to the fragility analyst as to what should be considered in developing a specific fragility description for a specific component.

●   an aid for interpreting and applying test data obtained from other sources. This is particularly valuable, for example, when using qualification data to assess actual component capacity or when consolidating equipment data from several sources.

- 18 -

- an improved basis for defining test conditions if more rigorous testing of a specific component or component type is required.

- guidance for developing screening techniques for reviewing actual plant equipment ("walkdown" procedures) and suggesting modifications for enhancing the seismic capacity of critical components.

It is also important that such testing be viewed not necessarily as a replacement for, but also as a supplement to, evaluation of data from other sources.

REFERENCES

1. G.S. Holman and C.K. Chou, et al., _Component Fragility Research Program: Phase I Component Prioritization_, Lawrence Livermore National Laboratory, NUREG report in preparation (September 1986).

2. G.S. Holman and C.K. Chou, _Component Fragility Research Program: Phase I Demonstration Tests_, Lawrence Livermore National Laboratory, NUREG report in preparation (May 1986).

3. R.J. Budnitz, et al., _An Approach to the Quantification of Seismic Margins in Nuclear Power Plants_, Lawrence Livermore National Laboratory, Report UCID-20444, NUREG/CR-4334 (August 1985).

Table 1. Systems identified according to plant safety function.

1. Reactivity Control

    1.1 Control Rod Insertion
    1.2 Accident Boration

2. Reactor Coolant Inventory Control

    2.1 Chemical and Volume Control System

        o   Letdown
        o   Charging (seal injection)

    2.2 Safety Injection Systems

        o   High-head injection
        o   Low-head injection
        o   Residual heat removal
        o   Core spray

    2.3 Reactor Coolant System (RCS) Pressure Relief

3. Reactor Coolant Pressure Boundary Integrity

    3.1 Reactor Coolant System
    3.2 RCS Pressure Relief System

4. Core Cooling

    4.1 Safety Injection Systems
    4.2 Residual Heat Removal System
    4.3 Main Steam (MS) System

5. Decay Heat Removal

    5.1 Auxiliary Feedwater System
    5.2 Reactor Coolant System
    5.3 RCS/MS Pressure Relief Systems
    5.4 Residual Heat Removal System

Table 1 (cont.). Systems identified according to plant safety
function.

_____

6. Plant Environment

    6.1 Containment Spray System
    6.2 Reactor Containment Fan Coolers
    6.3 Heating, Ventilating and Air Conditioning (HVAC) Systems
    6.4 Containment Purge System
    6.5 Containment Refrigeration System (ice condenser plants)

7. Containment Integrity

    7.1 Containment Isolation System
    7.2 Containment Spray System
    7.3 Containment Ventilation Systems
    7.4 Isolation Valve Seal Water System
    7.5 Penetration Pressurization System

8. Onsite Electrical Power

    8.1 Onsite AC Power System
    8.2 Onsite DC Power System

9. Instrumentation and Controls

    9.1 Instrument Air System
    9.2 Nuclear Instrumentation System (ex-core)
    9.3 Control Panels and Boards
    9.4 Local Instrumentation Racks
    9.5 Local Instruments
    9.6 Radiation Monitoring System
    9.7 Reactor Protection System
    9.8 Emergency Safety Function Sequencing System

10. Maintain Vital Auxiliaries

    10.1 Closed/Component Coolant Water System
    10.2 Service Water System
    10.3 Chilled Water System
    10.4 Fire Protection System

_____

Table 2. Summary of components ranked as "low-capacity" (Capacity Level 3).

_____

"Very Important" Components (Group VI-3)

        ESF sequencers
        Switchgear internals
        Motor control center internals
        Connections/mounting
        DC distribution switchboard internals
        Nuclear instrumentation equipment (ex-core)
        Electrical distribution equipment
        Ion chamber electrical connections
         P/P transducers
         P/P switches
        Temperature switches
        Flow switches
        Relays
        Process control equipment
        Mechanical/electrical interlocks
        Bistables
        Indicators/power supplies

"Important" Components (Group I-3)

        None identified

"Less Important" Components (Group LI-3)

        Rod bottom indicators
        Air handling units

_____

Table 3. Summary of components ranked as "intermediate-capacity" (Capacity Level 2).

_____

"Very Important" Components (Group VI-2)

 Reactor trip breakers
 Pilot-operated relief valves
 Safety valves
 Atmospheric dump valves
 Motor control center internals
 Batteries/battery racks
 ESF/RPS actuation cabinet internals
 Local instrument racks
 Control panels/boards internals
 Limit switches
 Air compressors
 Bearing cooling system equipment
 Fire detection devices
 Fire deluge equipment

"Important" Components (Group I-2)

 Seal injection filters
 Pressure relief valves (BWR)
 Vacuum relief valves
 Reactor coolant pump seals
 Louvers
 Air filters
 Radiation monitoring equipment
 Chiller units
 Strainers

"Less Important" Components (Group LI-2)

 Rod bottom indicators
 Dampers

_____

Table 4. Summary of components ranked as "high-capacity" (Capacity Level 1).

_____

"Very Important" Components (Group VI-1)

    Control rod drive equipment (BWR)
    Charging pumps and drives
    Motor-operated valves
    Check valves
    Explosive valves (BWR)
    Air-operated flow control valves
    Isolation valves
    Safety injection pumps and drives
    Residual heat removal pumps and drives
    Core spray pumps and drives
    Air-operated solenoid valves
    Main steam isolation valves
    Motor-operated flow control valves
    Auxiliary feedwater pumps and drives
    Containment spray pumps and drives
    Exhaust fans and drives
    Component cooling water pumps and drives
    Butterfly valves
    Air-operated valves
    Air-operated pressure control valves
    Diesel generators
    Diesel oil pumps and valves
    Diesel air accumulator
    Diesel lube oil equipment
    Combustion air intake louvers
    Isolation amplifiers
    Transformers
    Inverters

"Important" Components (Group I-1)

    Supply fans and valves

"Less Important" Components (Group LI-1)
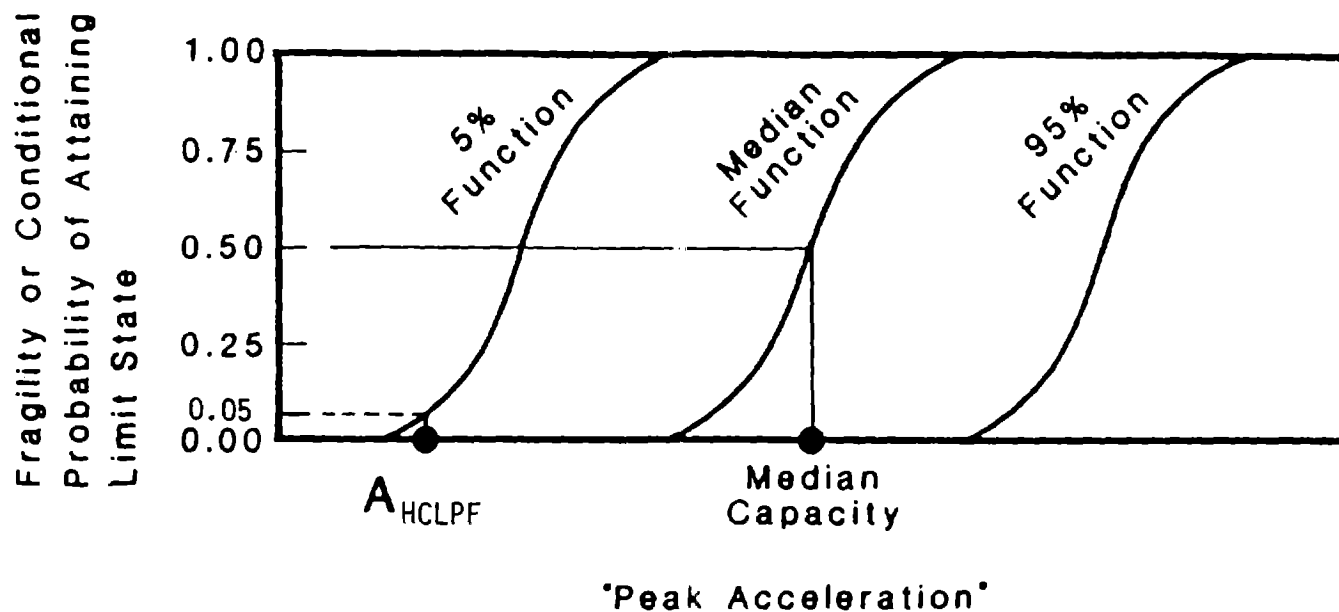
    None identified

_____

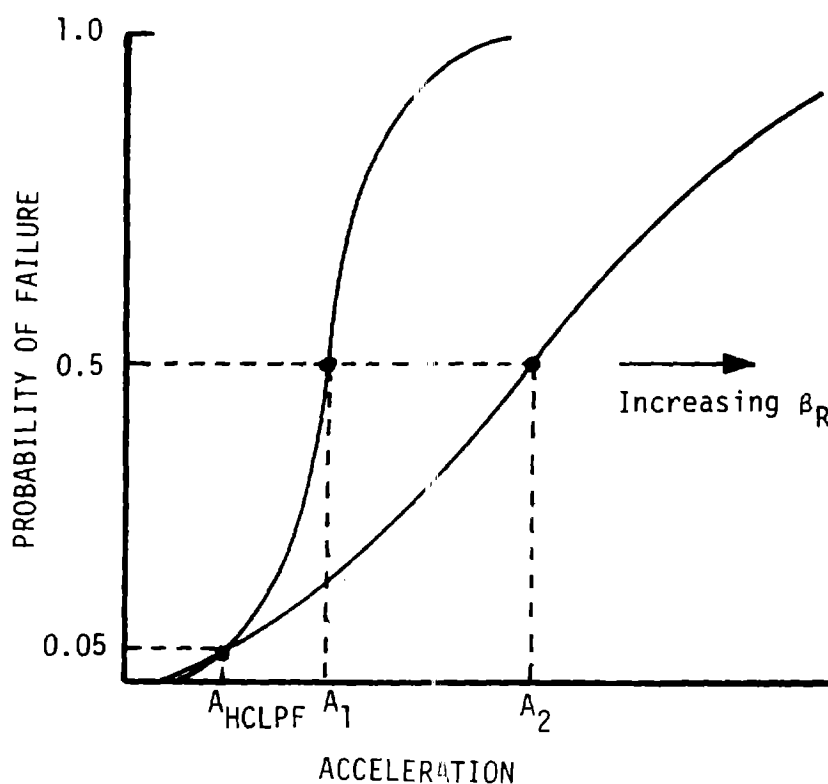Fig. 1. Typical curve set representing component fragility.

Fig. 2. Typical 5% fragility function showing how increasing random uncertainty affects median capacity derived from a HCLPF value. For constant β_U, the inferred fragility level of the component (i.e., median capacity of the 50% function) would be similarly affected.
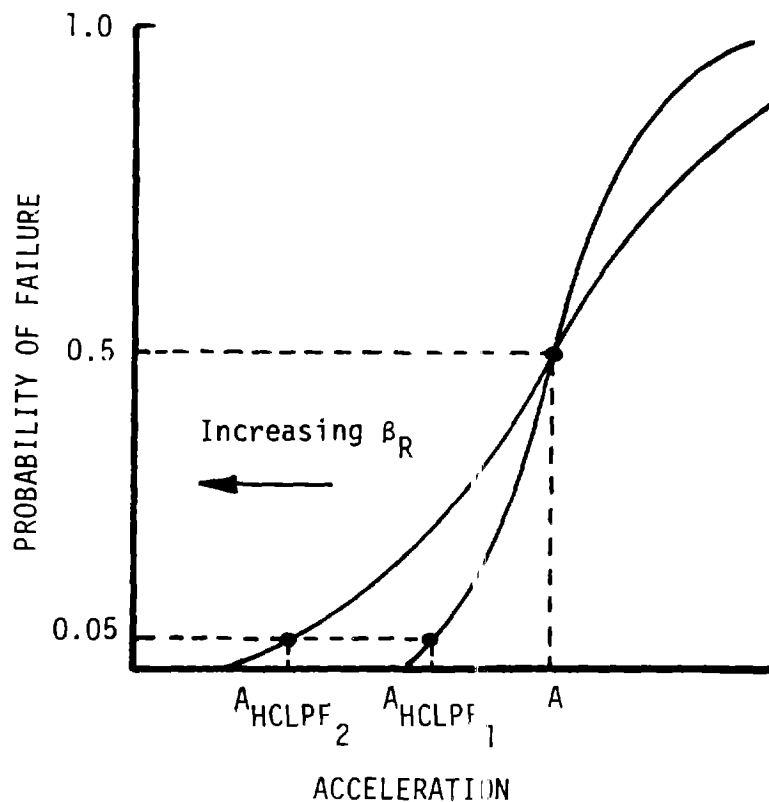
Fig. 3. Typical 5% fragility function showing how increasing random uncertainty affects the HCLPF value derived from a constant median capacity. For constant β_U, the effect would be the same for HCLPF values derived from a constant component fragility level.
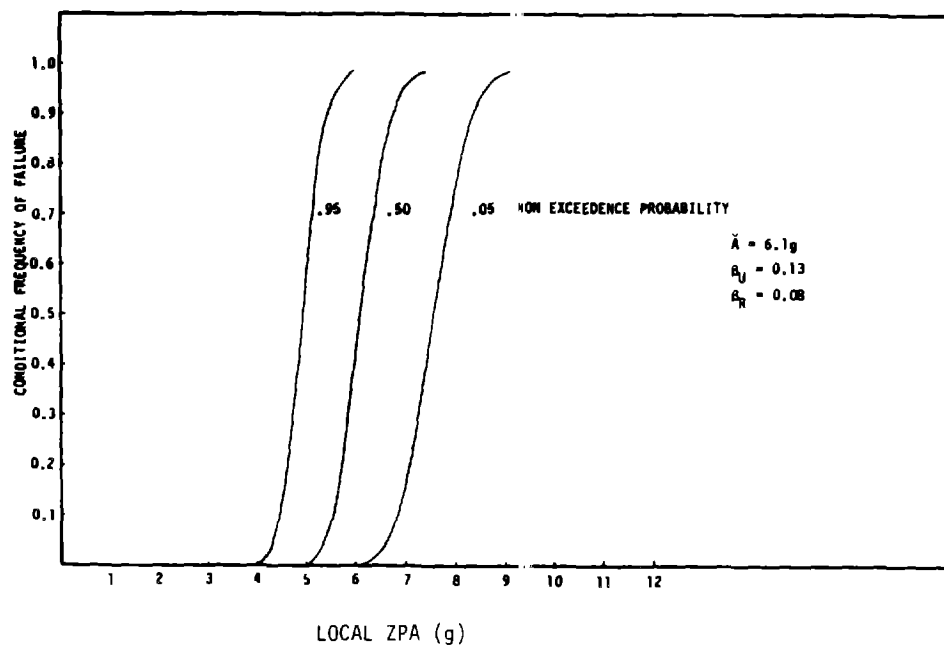

Fig. 4. Fragility curves for Westinghouse Type AR relays.